

Effect of bulk lubricant concentration on the excess surface density during R123 pool boiling

M.A. Kedzierski*

National Institute of Standards and Technology, Building 226, Room B114, Gaithersburg, MD 20899 USA

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Abstract

This paper investigates the effect that bulk lubricant concentration has on the non-adiabatic lubricant excess surface density on a roughened, horizontal flat (plain) pool-boiling surface. Both pool boiling heat transfer data and lubricant excess surface density data are given for pure R123 and three different mixtures of R123 and a naphthenic mineral oil. A spectrofluorometer was used to measure the lubricant excess density that was established by the boiling of a R123/lubricant mixture on a test surface. The fluorescent technique was used to measure the effect of bulk lubricant concentration on the lubricant excess layer during refrigerant/lubricant mixture boiling. The refrigerant preferentially boils, thus, concentrating and accumulating the lubricant on the surface in excess of the bulk concentration. The excess lubricant resides in a very thin layer on the surface and influences the boiling performance. Accordingly, the ability to measure the effect of bulk lubricant composition on the lubricant excess density and in turn the effect on the heat transfer would lead to a fundamental understanding of the mechanism by which lubricants can degrade or improve boiling performance. In support of this effort, heat transfer data are provided for pure R123 and three R123/lubricant mixtures at 277.6 K. For heat fluxes between approximately 25 to 45 kW/m², an average enhancement of the heat flux of 9 and 5% was achieved for the 0.5 and 1% lubricant mass fractions, respectively, and an average degradation of 5% in the heat flux was obtained for the 1.8% lubricant mass fraction mixture. © 2002 Published by Elsevier Science Ltd and IIR.

Keywords: Heat transfer; Mass transfer; Pool boiling; Mixture; Lubricant; Concentration; Density; Surface

R123 en ébullition libre : effet de la concentration globale en lubrifiant sur l'accroissement de sa densité superficielle

Mots clés : Transfert de chaleur ; Transfert de masse ; Ébullition libre ; Mélange ; Lubrifiant ; Concentration ; Densité ; Surface

* Tel.: +301-975-5282; fax: +301-975-8973.

E-mail address: mark.kedzierski@nist.gov

Nomenclature			
<i>English symbols</i>		y	test surface coordinate perpendicular to surface (m)
A	regression constants in Table 1	<i>Greek symbols</i>	
D	regression constants in Table A1	Γ	surface excess
F	fluorescence intensity	ΔT_s	wall superheat: $T_w - T_s$ (K)
F_c	fluorescence intensity from calibration [Eq. (2) of [2]]	ΔT_{ic}	temperature drop across excess layer (K)
F_m	fluorescence intensity measured from boiling surface	ε	extinction coefficient (m ² /mol)
I_o	incident intensity (V)	ζ	fraction of excess layer removed per bubble
k_L	thermal conductivity of pure lubricant (W/m K)	θ	dimensionless temperature profile Eq. (A.2)
l	path length (m)	λ	thermal boundary constant in Eq. (A.2)
l_e	thickness of excess layer (m)	ρ	mass density of liquid (kg/m ³)
M_L	molar mass of lubricant (kg/mol)	<i>English subscripts</i>	
q	average wall heat flux (W/m ²)	b	bulk
r_b	bubble departure radius (m)	e	excess layer
T	temperature (K)	L	lubricant
T_w	temperature at roughened surface (K)	m	measured
U	expanded uncertainty	p	pure R123
x	mass fraction of lubricant	r	refrigerant
		s	saturated state
		v	vapor

1. Introduction

The addition of lubricant to refrigerant can significantly alter the boiling performance due to lubricant accumulation at the heat transfer surface. Stephan [1] was one of the first researchers to note that a lubricant-rich layer exists near the tube wall. This mass of lubricant on the surface—the excess layer—is induced primarily by heat transfer. Non-boiling mechanisms such as long-range van der Waals forces contribute a relatively small mass, approximately one or two monolayers, to the lubricant excess layer. In general, the excess concentration (excess surface density) arises chiefly from the relatively low vapor pressure of the lubricant when compared to refrigerant. The lubricant is locally concentrated as a consequence of refrigerant evaporation at the heat transfer surface. The refrigerant/lubricant liquid mixture travels to the heated wall, and the refrigerant preferentially evaporates from the surface leaving behind a liquid phase enriched in lubricant. A balance between deposition and removal of the lubricant establishes some unknown thickness of the excess lubricant at the surface. It is hypothesized that the lubricant excess layer establishes the bubble size, the site density and, in turn, the magnitude of the heat transfer.

Kedzierski [2,3] developed a fluorescence measurement technique to verify the existence of the lubricant excess layer during pool boiling. A spectrofluorometer was specially adapted for use with a bifurcated optical bundle so that fluorescence measurements could be made perpendicular to the heat transfer surface. The

study suggested that the excess layer was pure lubricant with a thickness ranging from 0.04 to 0.06 mm depending on the heat flux. The study examined only one refrigerant/lubricant mixture.

The present study uses the measurement technique to extend the database to three R123/York-CTM1 mixtures with different mass compositions: 99.5/0.5, 99/1, and 98.2/1.8. In the present study, pure R123 and R123/lubricant mixtures were tested in an effort to investigate the influence of bulk lubricant concentration on the lubricant excess surface density. A 300 SUS naphthenic mineral oil (York-CTM) was chosen for its somewhat favorable fluorescence characteristics and to demonstrate the use of the new measurement technique with a commercial lubricant.

2. Apparatus

Descriptions of the pool boiling apparatus, the plain roughened copper test surface, and the spectro-

¹ Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

fluorometer are given in Ref. [4]. The test surface was an oxygen-free high-conductivity (OFHC) copper flat (plain) plate that was machined out of a single piece of copper by electric discharge machining (EDM). A tub grinder was used to finish the heat transfer surface of the test plate with a crosshatch pattern. Average roughness measurements were used to estimate the range of average cavity radii for the surface to be between 12 and 35 μm . The relative standard uncertainty of the cavity measurements were approximately $\pm 12\%$.

The spectrofluorometer that was used to make the fluorescence measurements is described in Refs. [2,3]. A bifurcated optical bundle with 168 fibers spanning from the spectrofluorometer to the test surface. The fibers of the probe were split evenly between the fibers to transmit the incident intensity (I_o) to the test surface and those to receive the fluorescence intensity (F) from the lubricant on the test surface.

3. Measurements and uncertainties

The individual standard uncertainties are combined to obtain the expanded uncertainty. The expanded uncertainty is calculated from the law of propagation of uncertainty with a coverage factor. All measurement uncertainties are reported for a 95% confidence interval except where specified otherwise.

3.1. Heat transfer

The heat transfer measurement techniques and uncertainties are given in Ref. [4].

3.2. Fluorescence

Kedzierski [2,3] describes the method for calibrating the emission intensity measured with the spectrofluorometer and the bifurcated optical bundle. The calibration and methodology that were outlined in these publications were used in the present study.

The equation for calculating the surface excess density (Γ) from the measured fluorescence emission intensity (F_m) for the York-CTM lubricant of minimum thickness is [3]:

$$\begin{aligned} \Gamma &= \rho_c N_c l_c - \rho_b N_b l_b \\ &= \frac{\rho_b N_b \left(1 - \frac{\rho_b N_b}{\rho_L}\right) \left(\frac{F_m}{F_c} - 1\right)}{\frac{I_{oc}}{I_{ob}} \left(1 + 1.165 \frac{\varepsilon}{M_L} N_b \rho_b l_b\right) \frac{1}{l_b} - 1.165 \frac{\varepsilon}{M_L} N_b \rho_b \left(\frac{F_m}{F_c} - 1\right)} \end{aligned} \quad (1)$$

where the value of $\frac{\varepsilon}{M_L}$ was obtained from the fluorescence calibration as $1.089 \text{ m}^2/\text{kg}$. The fluorescent inten-

sity from the calibration (F_c) is obtained from Eq. (2) of [2] evaluated at the charged bulk lubricant concentration of test fluid in the boiling apparatus. The l_b is the distance between the probe and the heat transfer surface and $l_b \gg l_c$. The density of the pure lubricant is ρ_L . The ratio of the absorption of the incident excitation in the bulk to that in the excess layer (I_{oc}/I_{ob}) was obtained from the measured absorption spectrum of a 95/5 mass fraction mixture of R123 and York-CTM. Absorption ratios for the 99.5/0.5, the 99/1, and the 98.2/1.8 mixtures were 0.9, 0.82, 0.71, respectively.

4. Experimental results

4.1. Heat transfer

The heat flux was varied from approximately 80 to 10 kW/m^2 to simulate typical operating conditions of R123 chillers. All pool-boiling tests were taken at 277.6 K saturated conditions. The data were recorded consecutively starting at the largest heat flux and descending in intervals of approximately 4 kW/m^2 . The descending heat flux procedure minimized the possibility of any hysteresis effects on the data, which would have made the data sensitive to the initial operating conditions. Kedzierski [4] tabulates the measured heat flux and wall superheat for all the data of this study. Table 1 gives the constants for the cubic regression of the superheat versus the heat flux for each data set. The residual standard deviation of the regressions representing the proximity of the data to the mean—are given in Table 2. Table 3 provides the average mean wall uncertainty for all of the test data.

The R123/mixture was prepared by charging the purger of the test apparatus with pure R123 to a known mass. Next, a measured weight of York-CTM was injected with a syringe through a port in the test chamber. The lubricant was mixed with R123 by flushing pure R123 through the same port where the lubricant was injected and releasing the R123 from the purger. All compositions were determined from the masses of the charged components and are given on a mass percent basis. The maximum uncertainty of the composition measurement is approximately 0.02%, e.g. the range of a 1.8% composition is between 1.78 and 1.82%.

Fig. 4 of Kedzierski [2] present the measured heat flux (q) versus the measured wall superheat ($T_w - T_s$) for pure R123 at a saturation temperature of 277.6 K. Fig. 5 of Kedzierski [2] shows the q versus the measured wall superheat for the 98.2/1.8 R123/ York-CTM mixture. Figs. 1 and 2 of this study plot the measured heat flux versus the measured wall superheat at a saturation temperature of 277.6 K for the 99.5/0.5 and the 99/1 York-CTM mixtures, respectively. The mean of the pure R123 “aged data” is plotted as a dashed line. In Fig. 1, com-

Table 1

Constants for cubic boiling curve fits for flat copper surface: $\Delta T_s = A_0 + A_1 q'' + A_2 q''^2 + A_3 q''^3$; ΔT_s in Kelvin and q'' in W/m^2

Fluid		A_0	A_1	A_2	A_3
R123	$\Delta T_s \geq 13 \text{ K}$	7.71421	4.17449×10^{-4}	-7.45117×10^{-9}	4.69661×10^{-14}
Break-in data	$\Delta T_s \leq 13 \text{ K}$	4.34389	-3.67068×10^{-4}	8.26988×10^{-8}	-2.14203×10^{-12}
R123	$\Delta T_s \geq 18 \text{ K}$	32.2044	3.20480×10^{-3}	-6.42276×10^{-8}	4.28317×10^{-13}
	$\Delta T_s \leq 18 \text{ K}$	25.3837	-2.12686×10^{-3}	9.53098×10^{-8}	-1.11703×10^{-12}
R123a/York-C TM	$\Delta T_s \geq 19 \text{ K}$	51.792	-2.54999×10^{-3}	6.33178×10^{-8}	-4.90908×10^{-13}
(99.5/0.5)	$\Delta T_s \leq 20 \text{ K}$	1.50894	5.02619×10^{-4}	3.77597×10^{-9}	-1.24206×10^{-13}
R123a/York-C TM		0.82896	7.87921×10^{-4}	-5.22161×10^{-9}	-3.32047×10^{-14}
(99/1) $11 \text{ K} \leq \Delta T_s \leq 21.5 \text{ K}$					
R123a/York-C TM (98.2/1.8)		2.98244	3.88456×10^{-4}	9.51211×10^{-9}	-1.92371×10^{-13}
$9 \text{ K} \leq \Delta T_s \leq 22.5 \text{ K}$					

parison of the 99.5/0.5 mixture boiling curve to the mean R123 boiling curve shows that there is little difference between the curves for superheats below 17 K. However, the heat transfer performance of 99.5/0.5 refrigerant/lubricant is greater than that of the pure refrigerant for superheats between 17 and 21 K. Similarly, the 99/1 mixture boiling curve shown in Fig. 2 illustrates that there is little difference between the pure and mixture curves for superheats below 15 K. However, the heat transfer performance of the 99/1 refrigerant/lubricant is greater than that of the pure refrigerant for superheats between 15 and 21 K. Fig. 5 of [2] shows that the mean heat transfer performance of the 98.2/1.8 refrigerant/lubricant mixture is less than that of the pure refrigerant for all superheats. Figs. 1, 2 and 5 of [2] also show the results of a prediction method, which is discussed in the preceding and developed in Appendix A, that uses the excess layer data as input.

A more detailed comparison of the mixture and the pure fluid heat transfer performance is given in Fig. 3. Fig. 3 plots the ratio of the mixture to the pure R123 heat flux (q_m/q_p) versus the pure R123 heat flux (q_p) at the same wall superheat. A heat transfer enhancement exists where the heat flux ratio is greater than one and the 95% simultaneous confidence intervals (depicted by shaded region) do not include the ratio of one. Fig. 3 shows that the R123/York-CTM (99.5/0.5) mixture exhibits an enhancement for heat fluxes greater than approximately 26 kW/m^2 and less than approximately 45 kW/m^2 . The cessation of vigorous nucleate boiling (CVNB) was visually observed to be located near 26 kW/m^2 . Consequently, the addition of York-CTM to R123 improves the heat transfer associated with vigorous boiling more so than it does for low-active-site-density boiling region. The maximum heat flux ratio for the 99.5/0.5 mixture was 1.136 ± 0.015 at 35.6 kW/m^2 . The average heat flux ratio for the R123/York-CTM (99.5/0.5) mixture from approximately 25 to 45 kW/m^2 was 1.09.

Table 2

Residual standard deviation of ΔT_s from the mean

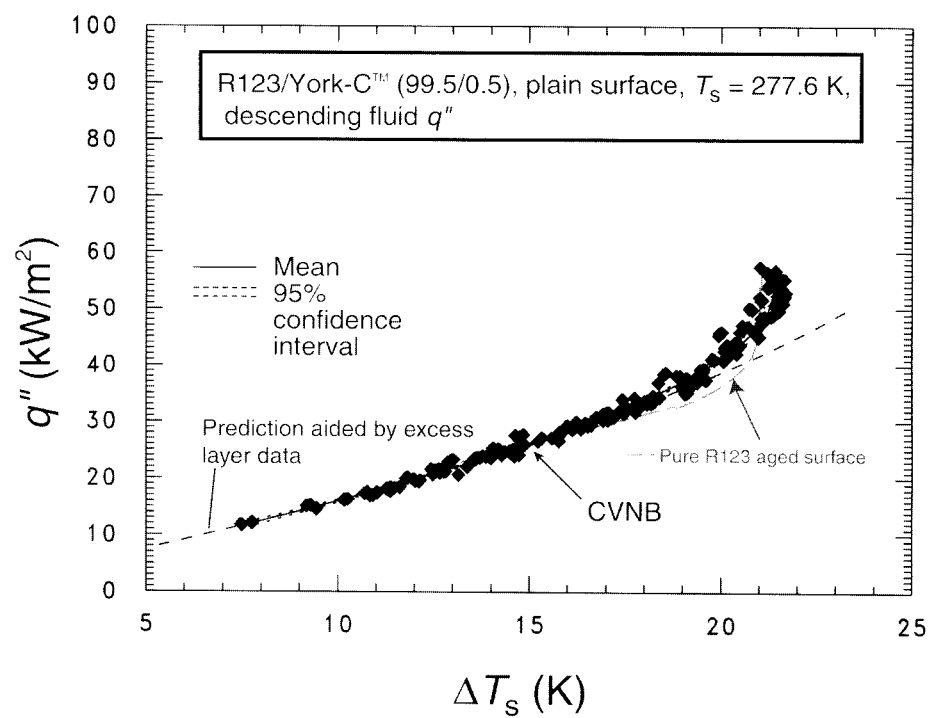
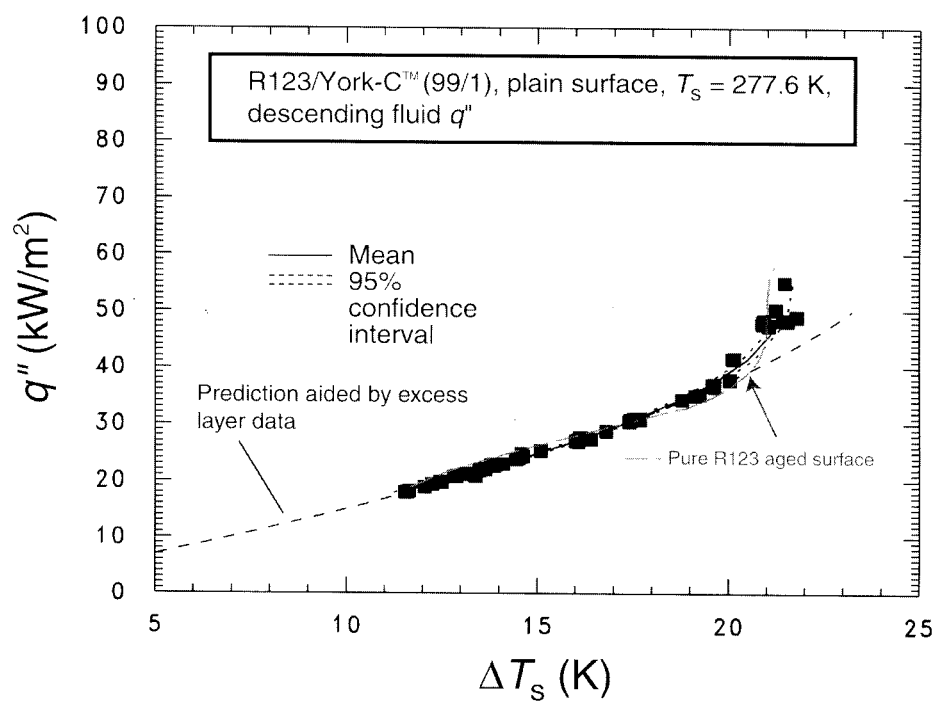
Fluid		U (K)
R123	$\Delta T_s \geq 13 \text{ K}$	0.31
Break-in data	$\Delta T_s \leq 13 \text{ K}$	0.19
R123	$\Delta T_s \geq 18 \text{ K}$	0.20
	$\Delta T_s \leq 18 \text{ K}$	0.47
R123a/York-C TM	$\Delta T_s \geq 19 \text{ K}$	0.25
(99.5/0.5)	$\Delta T_s \leq 20 \text{ K}$	0.33
R123a/York-C TM (99/1)		0.20
$11 \text{ K} \leq \Delta T_s \leq 21.5 \text{ K}$		
R123a/York-C TM (98.2/1.8)		0.48
$9 \text{ K} \leq \Delta T_s \leq 22.5 \text{ K}$		

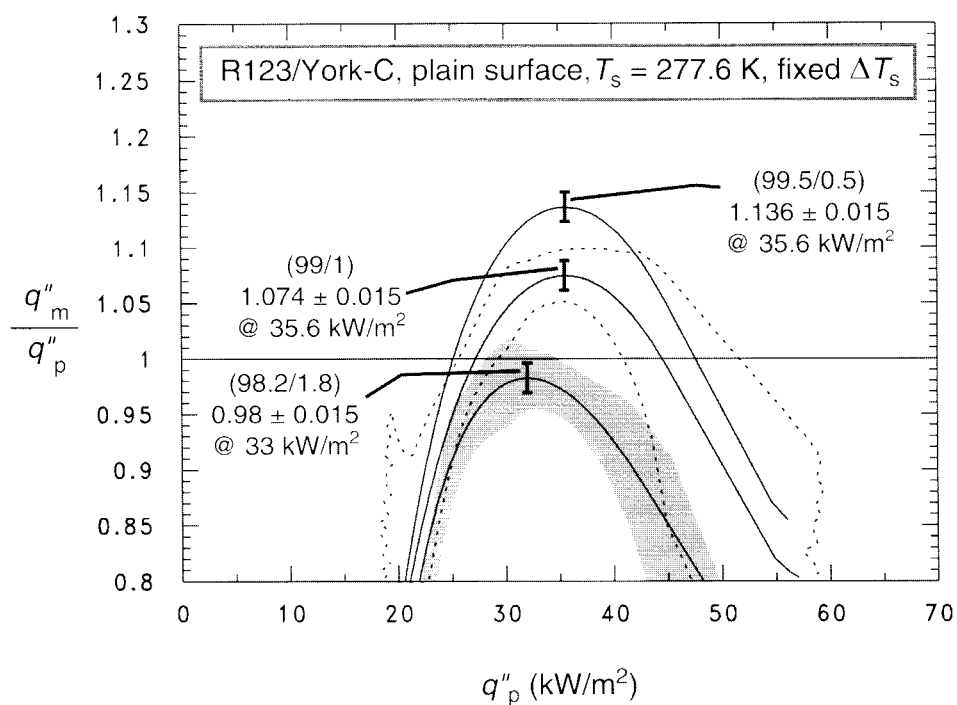
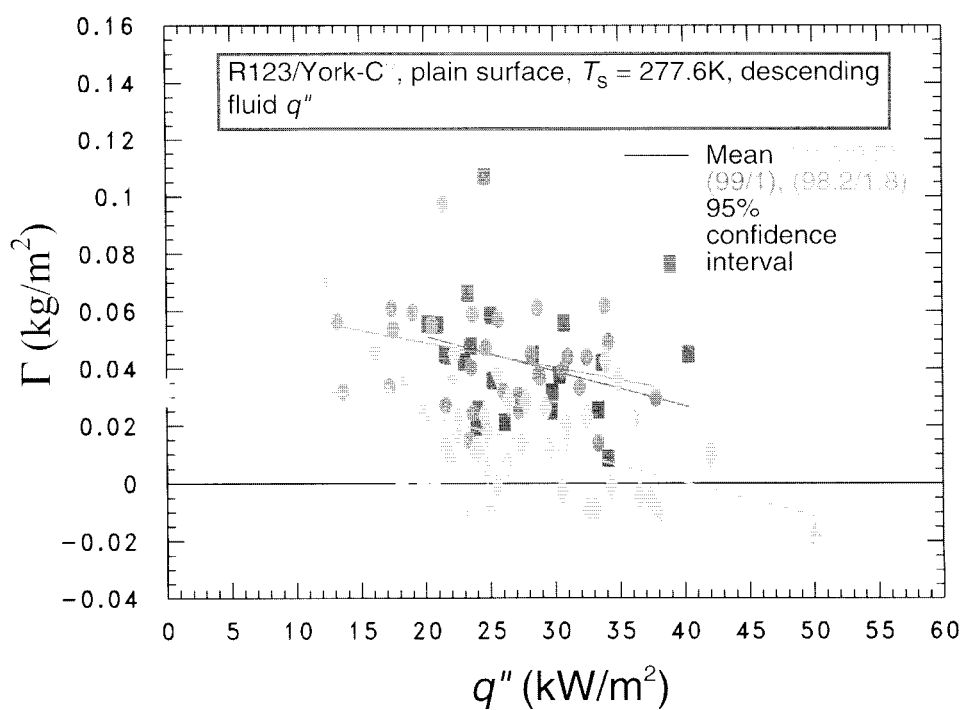
Table 3

Average magnitude of 95% multi-use confidence interval for mean T_w , T_s (K)

Fluid		U (K)
R123	$\Delta T_s \geq 13 \text{ K}$	0.17
Break-in data	$\Delta T_s \leq 13 \text{ K}$	0.28
R123	$\Delta T_s \geq 18 \text{ K}$	0.20
	$\Delta T_s \leq 18 \text{ K}$	0.67
R123a/York-C TM	$\Delta T_s \geq 19 \text{ K}$	0.18
(99.5/0.5)	$\Delta T_s \leq 20 \text{ K}$	0.15
R123a/York-C TM (99/1)		0.13
$11 \text{ K} \leq \Delta T_s \leq 21.5 \text{ K}$		
R123a/York-C TM	$\Delta T_s \geq 4.4 \text{ K}$	0.24
(98.2/1.8)	$\Delta T_s \leq 4.4 \text{ K}$	

Fig. 3 shows that the R123/York-CTM (99/1) mixture exhibits an enhancement for heat fluxes greater than approximately 28 kW/m^2 and less than approximately 43 kW/m^2 . The CVNB was visually observed to be located near 26 kW/m^2 . Consequently, the enhancement characteristics of the 99/1 mixture are consistent with

Fig. 1. R123 York-CTM (99.5/0.5) boiling curve for plain surface.Fig. 2. R123 York-CTM (99/1) boiling curve for plain surface.

Fig. 3. R123 York-C^{1M} (98.2/1.8) heat reflux relative to that of pure R123.Fig. 4. Lubricant excess surface density for three R123 York-C^{1M} mixtures as a function of heat flux.

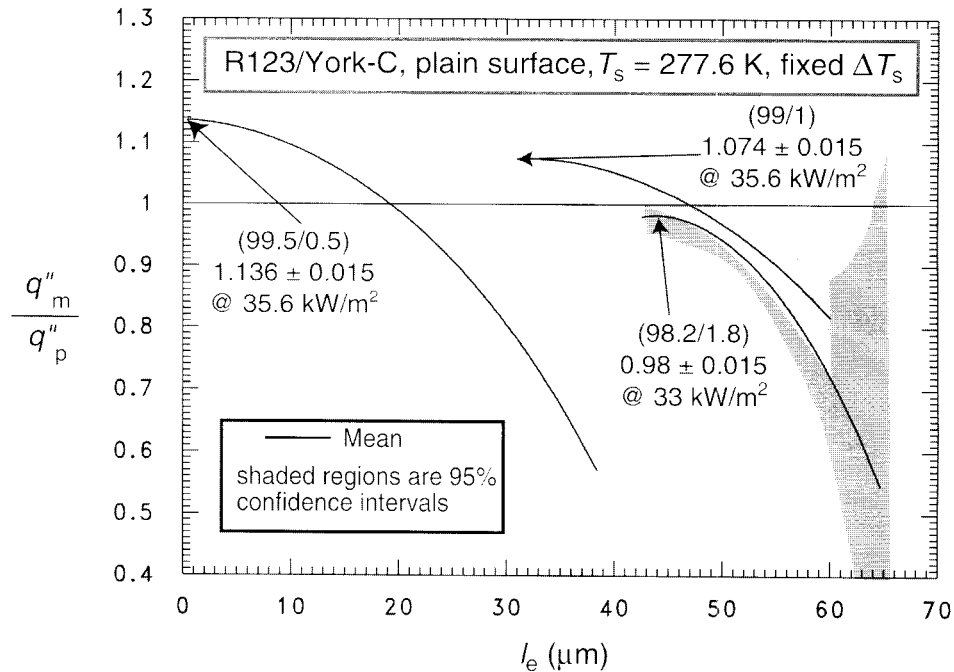


Fig. 5. Influence of excess layer thickness on R123/York-CTM relative heat flux.

those for the 99.5/0.5 mixture in so much that it is the vigorous boiling region that is enhanced. The maximum heat flux ratio for the 99/1 mixture was 1.074 ± 0.015 at 35.6 kW/m^2 . The average heat flux ratio for the R123/York-CTM (99/1) mixture from approximately 25 to 45 kW/m^2 was 1.05.

Fig. 3 shows that the R123/York-CTM (98.2/1.8) mixture exhibits a degradation for all the heat fluxes that were tested with the exception of heat fluxes between 28 and 35 kW/m^2 where the heat transfer may not differ from the pure refrigerant. The CVNB for the mixture was visually observed to be located near 26 kW/m^2 . Recall that the CVNB for pure R123 occurred at approximately 35 kW/m^2 . Consequently, the addition of York-CTM to R123 enhances the boiling site density but this is not sufficient to cause an overall enhancement of the boiling performance due to the reduction in bubble size with lubricant addition. The maximum heat flux ratio for the 98.2/1.8 mixture was 0.98 at 33 kW/m^2 . The average heat flux ratio for the R123/York-CTM (98.2/1.8) mixture from approximately 25 to 45 kW/m^2 was 0.95.

4.2. Fluorescence

Fig. 4 is a plot of the measured lubricant excess density versus the heat flux for the three R123/York-CTM mixtures. Solid lines represent the mean of the data. The

shaded regions are 95% confidence intervals for the mean. The green, red, and blue lines, symbols, and shading correspond to the 99.5/0.5, the 99/1, and the 98.2/1.8 compositions, respectively. The expanded uncertainty of the lubricant excess density was estimated from the multi-use confidence intervals to be 0.01, 0.02, and 0.014 kg/m^2 for the 99.5/0.5, the 99/1, and the 98.2/1.8 compositions, respectively. Table A1 in Appendix A provides the residual standard deviation for the Γ fit for each mixture.

The lubricant excess density is roughly the mass of lubricant in the excess layer per surface area in excess of the lubricant contribution from the bulk. Consequently, $\Gamma = 0$ implies that no excess layer exists on the surface. Considering this, Fig. 4 substantiates the existence of the lubricant excess layer for most of the data because most of the data, its mean, and the confidence intervals for the mean are all greater than zero. The data does not confirm the existence of the excess layer for the 99.5/0.5 mixture for heat fluxes greater than 33 kW/m^2 .

Fig. 4 shows that an increase in bulk lubricant concentration increases the mass of lubricant on the surface to a point. For example, at a heat flux of 23 kW/m^2 , the lubricant excess layer increased from approximately 0.02 to 0.05 kg/m^2 when the bulk lubricant mass fraction was doubled, i.e. increased from 0.005 to 0.01. However, when the bulk lubricant mass fraction was nearly doubled again (increased from 0.01 to 0.018) no further increase in the lubricant excess density was

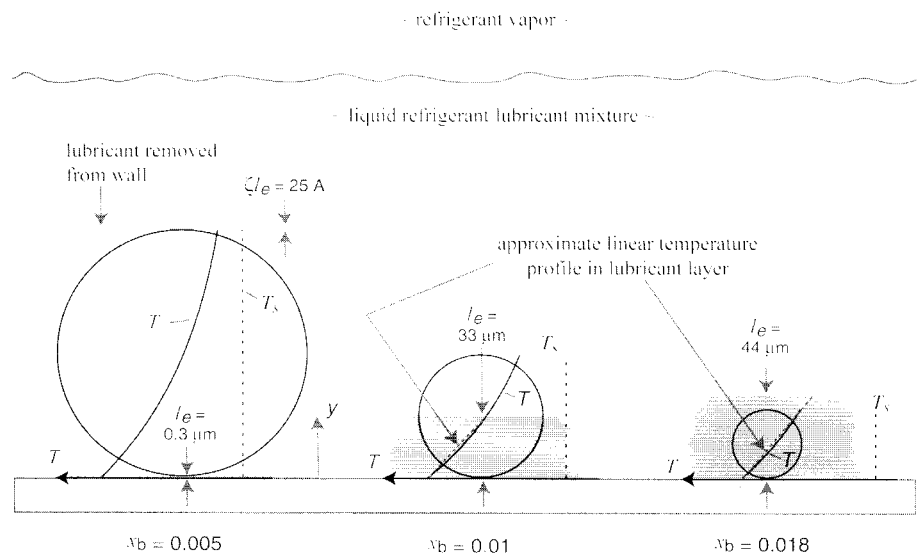


Fig. 6. Schematic of the average departure bubble for three R123 York-CTM mixtures with corresponding excess layers.

observed. This may suggest an upper limit for the mass of lubricant that can be maintained in the excess layer. In addition, during the formation of the excess layer, the removal of lubricant for the 0.018 mass fraction mixture must occur at either a much greater rate or with a much different dependence with time than the 0.01 mass fraction mixture for the steady state Γ to remain unchanged.

5. Discussion

Fig. 5 illustrates the influence of the excess layer thickness on the normalized heat flux (q''_m/q''_p) for the range of measured l_e . The values shown in the figure for both the relative heat flux and the thickness are the means of the regressed data for the three mixtures of this study. The maximum heat flux enhancement corresponds closely to the minimum observed excess layer thickness relative to the size of the bubble for each mixture. Consistent with intuition, a build up of lubricant on the surface is detrimental to pool boiling performance.

The importance of the excess layer thickness on pool boiling can be further illustrated with the use of a simple semi-empirical model for refrigerant/lubricant mixtures. The model was developed to show how the lubricant layer can adversely affect heat transfer by flooding the bubble with lubricant. Appendix A provides the details of the model development, which involves both heat transfer and excess density data. Fig. 6 shows a schematic of the average departure bubble for each of the three mixtures at the maximum heat flux ratio for

each mixture. Note that the model correctly predicts that the departure diameter decreases with increasing lubricant in the bulk liquid [5]. The (99.5/0.5) mixture is shown to have nearly the entire bubble diameter in the bulk fluid. Here, the excess layer thickness is two orders of magnitude smaller than the excess layer for the (99/1) mixture. The (99/1) mixture is shown to have approximately half of its departure bubble diameter within the lubricant excess layer. The departure bubble for the (98.2/1.8) mixture forms entirely within the lubricant excess layer. Presumably, heat transfer performance suffers as more lubricant must be displaced from the wall in order to make way for the fresh bulk refrigerant.

6. Conclusions

A newly developed fluorescent measurement technique was used to investigate the effect of bulk lubricant concentration on the lubricant excess layer during boiling of R123 and a commercial lubricant (York-CTM). A spectrofluorometer was specially adapted for use with a bifurcated optical bundle so that fluorescence measurements could be made perpendicular to the heat transfer surface. The heat transfer surface was a horizontal, roughened, plain copper flat plate. Larger enhancements are associated with smaller lubricant excess layers relative to the size of the bubble. The lubricant excess surface density was shown to be the smallest for the smallest bulk concentration. The surface density was nearly the same for the two largest bulk concentrations. However, the boiling performance of the largest lubricant

concentration mixture was the worst of all the mixtures because its bubbles were the smallest of all the mixtures.

The boiling heat transfer measurements were simultaneously taken with the fluorescence measurements. The heat transfer performance of 99.5/0.5 refrigerant York-CTM was on average 9% greater than that of the pure refrigerant from approximately 25 to 45 kW/m². The heat transfer performance of the 99/1 refrigerant York-CTM was on average 5% greater than that of the pure refrigerant from approximately 25 to 45 kW/m². The R123/York-CTM (98.2/1.8) mixture heat flux from approximately 25 to 45 kW/m² was on average 5% less than that of pure R123.

Figs. 1, 2 and 5 of [2] compare the measured boiling curves for the three mixtures to the model given by Eq. (A3). The mean absolute difference between the predicted and measured mean wall superheat is 0.46, 0.07, and 0.22 K for the (99.5/0.5), (99/1), and (98.2/1.8) mixture, respectively. This comparison was made for the heat flux range for which excess surface density measurements were available. The value of the fitted constant λ was 1.74, 1.09, and 0.57 for the (99.5/0.5) mixture, the (99/1) mixture, and the (98.2/1.8) mixture, respectively.

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Appendix A

This Appendix outlines the development of a semi-empirical model for the prediction of refrigerant lubri-

cant pool boiling. The model is fitted to excess surface density and heat transfer measurements. The model relies on three key assumptions: (1) lubricant is lifted from the excess layer as lubricant caps on bubbles, (2) the temperature profile in the thermal boundary layer can be approximated with an exponential function, and (3) the temperature profile within the excess layer is linear.

Fig. 6 shows that each bubble removes a fraction (ζ) of the excess layer thickness (l_e) in a volume that is equivalent to that of a lubricant disk with a radius equal to the departure bubble (r_b) and thickness equal to ζl_e . The lubricant that is removed is assumed to reside on the top of the bubble as an adiabatic excess layer of approximately 2 monolayers thick [6], which is approximately 25 Å for lubricant with a liquid viscosity of York-CTM [7].

The lubricant excess layer is formed on the wall by preferential evaporation of the refrigerant. The present model assumes that all of the lubricant that is carried to the wall by the bulk liquid/lubricant mixture is deposited on the wall while all of the refrigerant leaves the wall as refrigerant vapor. Writing a mass balance between lubricant deposition and removal and rearranging to solve for the bubble radius yields:

$$r_b = \frac{0.75\zeta l_e \rho_l (1 - x_b)}{x_b \rho_{rv}} = \frac{18.75A \rho_l (1 - x_b)}{x_b \rho_{rv}} \quad (\text{A1})$$

where ρ_{rv} and ρ_l are the densities of the refrigerant vapor and the liquid lubricant, respectively.

Fig. 6 shows the temperature profile of the thermal boundary layer. The dimensionless form of the temperature profile (θ) was approximated by the following exponential function:

$$\theta = \frac{T - T_s}{T_w - T_s} = e^{-\lambda y / r_b} \quad (\text{A2})$$

Table A1

Constants for linear excess surface density fits for flat copper surface: $\Gamma = D_0 + D_1 q''$ (Γ in kg/m² and q'' in kW/m²)

Fluid	D_0	D_1	Residual standard deviation (kg/m ²)	Average 95% confidence interval (kg/m ²)
R123a/York-C TM (99.5/0.5) 12 kW/m ² $\leq q'' \leq$ 50 kW/m ²	0.04759	-1.18167×10^{-3}	0.017	0.01
R123a/York-C TM (99/1) 20 kW/m ² $\leq q'' \leq$ 40 kW/m ²	0.08056	-1.33541×10^{-3}	0.02	0.02
R123a/York-C TM (98.2/1.8) 13 kW/m ² $\leq q'' \leq$ 38 kW/m ²	0.06945	9.46412×10^{-4}	0.018	0.014

where T is the temperature of the fluid, y is a coordinate direction measured perpendicularly from the wall, and λ is a constant that is obtained for each mixture from a fit of the measured pool boiling curve.

Eq. (A2) is used to calculate the temperature drop in the lubricant excess layer (ΔT_{le}). If the temperature gradient in the excess layer is approximated as linear, Fourier's law can be rearranged to obtain the wall superheat (ΔT_s):

$$\Delta T_s = T_w - T_s = \frac{q'' l_c}{k_L(1 - e^{-\lambda l_c/r_b})} = \frac{q'' \Gamma}{k_L(1 - e^{-\lambda l_c/r_b})(\rho_l - \rho_b N_b)} \quad (A.3)$$

where k_L is the thermal conductivity of the lubricant, and linear fits of the excess surface density are given in Table A1. Table A1 also provides the residual standard deviations and the average multi-use 95% confidence intervals for the fits.

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